

## **SECTION 2 REEF SYSTEMS**

### **SUBSECTION 1 CIRCULATION, PLANKTON AND NUTRIENTS**

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## CIRCULATION IN ENEWETAK ATOLL LAGOON

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### ABSTRACT

Current measurements at Enewetak Atoll, Marshall Islands, were made on the reef margins, in the channels, and in the lagoon. Lagoon circulation is dominated by wind-driven downwind surface flow and an upwind mid-depth return flow. This wind-driven flow has the characteristics of an Ekman spiral in an enclosed area. Lagoon flushing is accomplished primarily by surf-driven water input over the windward (eastern) reefs and southerly drift out the South Channel. Mean water residence time in the lagoon is one month, while water entering the northern portion of the atoll takes about four months to exit.

Upwelling on the windward sides of deep atoll lagoons does not appear to be a general feature of lagoon circulation.

### INTRODUCTION

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Current measurements at Enewetak Atoll, Marshall Islands, were made on the reef margins, in the channels, and in the lagoon. Most measurements were made during a two month summer period and a two month winter period, however all observations span the period from 1971 to 1979 during all seasons of the year.

The location of the following current regimes are shown in Figure 1. Water flows in the lagoon from the windward reef, the Deep Entrance, and the Southwest Passage. The windward cross-reef current transports about twice as much water as the Deep Entrance current. It does not reverse as do the currents in the Deep Entrance and the Southwest Passage. Therefore, the water flow over the windward reef represents the only significant net input of water into the lagoon.

The water flows out of the lagoon from the leeward reef, the Deep Entrance, the South Channel, and the Southwest Passage. The Deep Entrance and the Southwest Passage have net transports near zero over each tidal cycle, so the net inflow from the windward reef must exit as outflow over the leeward reef and out the South Channel. The flow over the leeward reef is relatively small; therefore most of the water flows south to the South Channel. We have calculated that the average flow out of the South Channel represents 105% of the calculated input over the entire windward reef.

The entire water column therefore has a net flow toward the South Channel. Superimposed on this southward flow is the downwind and upwind flow created by the wind. The deeper flow spirals to the right of the shallower flow (Fig. 2). The shallow vertical current spiral resembles the flow pattern predicted by Ekman (1905) for an enclosed sea. These wind-driven currents are superimposed on the net flow of water toward the South Channel. The southward flow can be directly observed only in the deep water, below the layers affected by the wind, and in the South Channel itself. The right-handed current spiral can also be distorted by the currents near the lagoon perimeter (Fig. 2).

The average residence time of water in the lagoon is about one month. However, based on our findings that most of the water entering over northern reefs (about  $\frac{1}{4}$  of the total inflow), must transit the entire lagoon to exit from the South Channel, this water should have a residence time approximately four times longer than that for the lagoon as a whole. The residence time of northern lagoon water based on flushing rates of transuranic radionuclides supports the above conclusion (Noshkin, pers. comm.).

The circulation of water in Enewetak Atoll lagoon can be explained as a response to three driving mechanisms: (1) surf on the windward ocean reef, (2) wind stress on the lagoon surface, and (3) the tides.

(1) The breaking waves on the windward reef drive water over the windward reef and into the lagoon on the eastern (prevailing windward) side of the atoll. The cross-reef currents and the currents behind the reef are therefore dependent on the surf

height and the depth of water on the reef. This oceanic water spreads into the lagoon, moving downwind and mixing vertically and horizontally.

(2) The wind creates the downwind drift of the surface water and the upwind drift of the mid-depth water.

(3) The tidal currents directly influence the flow of water within several kilometers of the passes, especially in the southern part of the lagoon. These tidal currents can locally overwhelm the wind-

driven circulation, leading to such effects as the "left-handed" spiral observed one kilometer north of Enewetak Island (Fig. 2).

Our model for the circulation of Enewetak lagoon has similarities to the model proposed by von Arx (1948) for Bikini. In particular, both show downwind surface flow and a subsurface return.

The deep circulation, however, seems very different from that proposed by von Arx. We found deep flow moving southward toward the South

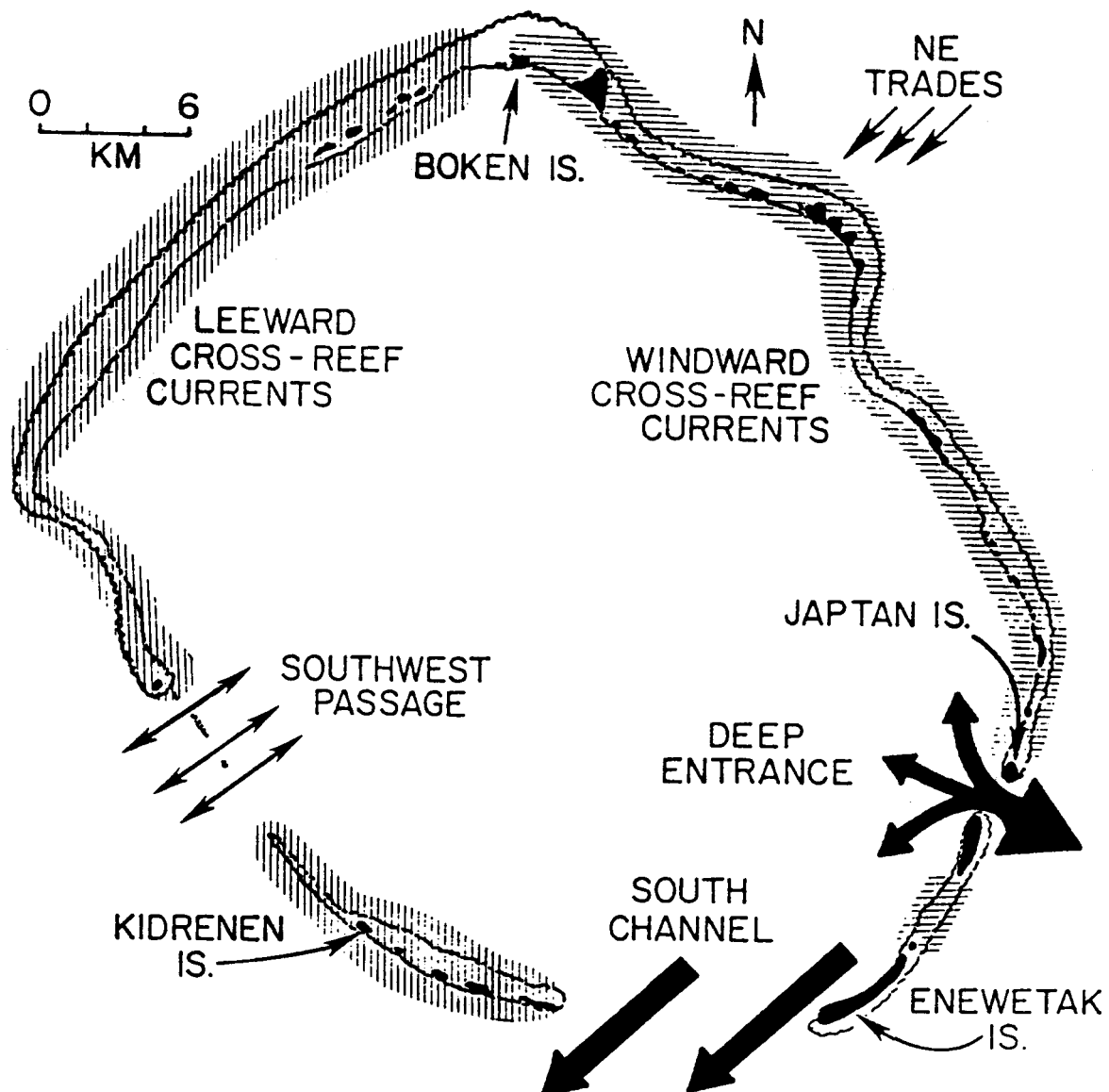


Figure 1. Location of the major current regimes of Enewetak Atoll. The central lagoon flows are not shown here but are illustrated in Fig. 2.

Channel; he described an upwind (eastward) deep flow with transport greater than that of the downwind surface flow. He therefore postulated continual upwelling on the windward, eastern, side of the lagoon. Upwelling will occur at Enewetak only if the cross-reef currents and Deep Entrance tidal currents cannot provide sufficient flow to offset the downwind surface flow.

In spite of the apparent discrepancy, we feel that both lagoons may be responding in fundamentally the same way. At Bikini, besides net outflow through the southwestern channels, we believe there is significant net outflow through the Enyu Channel near the eastern end of the atoll (recalculation of information given by von Arx 1948). This is also seen in surface radionuclide distribution

(Noshkin et al. 1974) and distribution of endemic zooplankton (Johnson 1949). In order to reach this exit the deep water in Bikini Lagoon must move eastward. In Enewetak the only effective exit is at the southernmost part of the atoll, so the deep water must move southward.

Note especially in this circulation model that the deep motion is primarily controlled by the location of the major exit-points from the lagoon. Water throughput of other shallower atoll lagoons appears dominated by atoll morphology and local wave and tide climate (Milliman 1967, Gallagher et al. 1971, Henderson et al. 1978, Ludington 1979). The role of wind-driven upwelling and sinking is greatly reduced from that in von Arx's model.

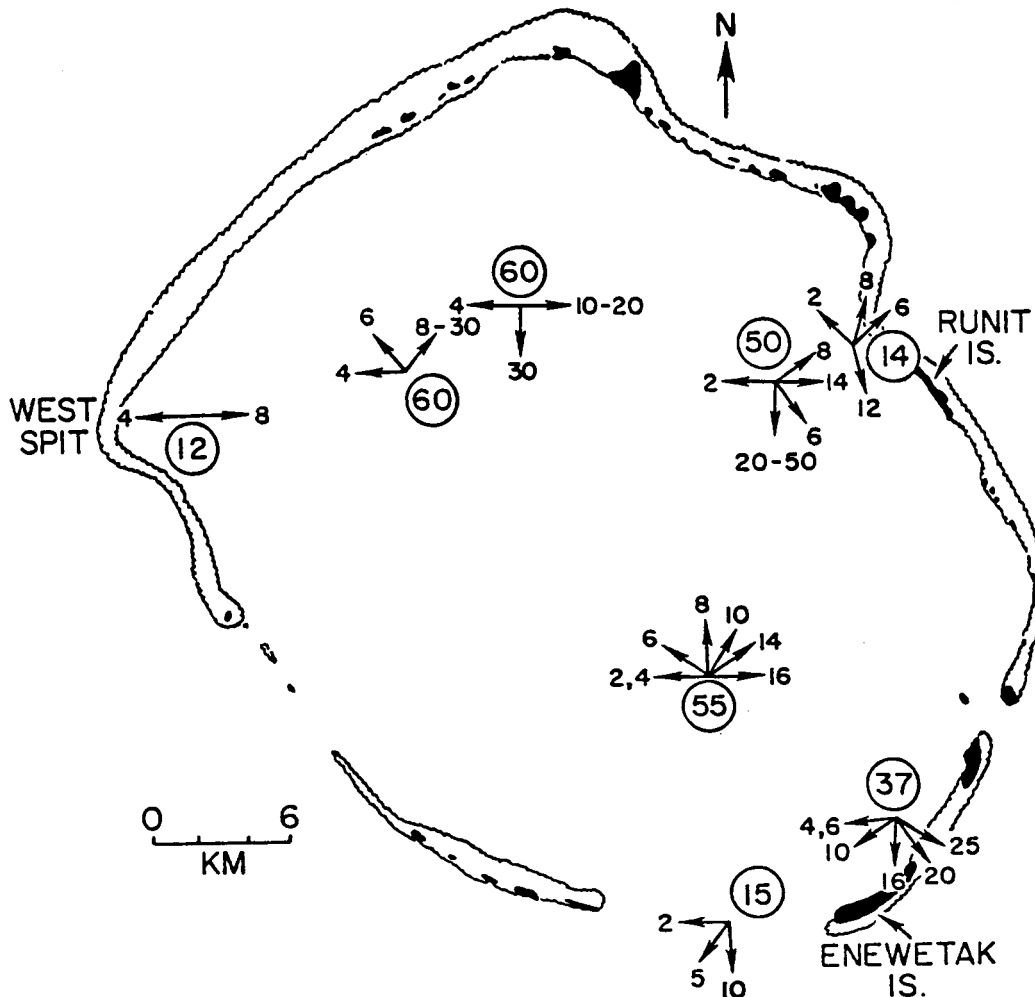


Figure 2. Vertical flow profiles using dye dispensers suspended on a vertical line. The arrow shows the direction of the flow and the number at the end of the arrow gives the depth in meters. Circled number is the bottom depth in meters. The wind blew from the east during the period measurements were made.

### CONCLUSIONS

Windward and leeward cross-reef currents, channel currents, and tidal flow are the major factors influencing exchange of water between all atoll lagoons and the surrounding ocean. These factors are specific to local wave climate, tidal conditions, and atoll morphology, resulting in widely varying flushing characteristics. Wind-driven circulation is a pervasive feature of lagoons, contributing primarily to internal circulation rather than to flushing. Upwelling on the windward side of the lagoon may occur as a summation of the above phenomena but does not seem to be a general feature of lagoon circulation. Deep water flow appears to orient itself toward the channels of net water output.

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